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This paper reviews performance of hybrid and monolithically integrated WDM transmitter arrays based on directly modulated 2.5 Gbps lasers, with a focus on the wavelength accuracy and stability under normal operating conditions. We also consider power stability, chromatic dispersion penslties, and the channel cross-talk. Large numbers of four-wavelength devices were obtained and evaluated under a program designed to provide university-based system researchs with advanced WDM components. We hsow that multi-wavelength laser arrays capable of high-performance out-of-the-box operation can be now produced for research-type WDM systems.

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Final Technical Report

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"A High Speed Bit Error Rate Test Set for Quantitative Evaluation of Optoelectronic Computer Networks"

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I. Project Description

The objective of this project was to acquire a high speed bit-error-tester to allow for quantitative evaluation of optical networks based on wavelength division multiplexing. Two competing sources of BERTs were evaluated, Anritsu and Hewlett Packard. We found these two suppliers to be very close in price and performance. Both units offered testing at data rates as high as 12 Gb/s. The unit offered by HP had better software control and allowed for automatic eye plots and Q analysis. It also allowed for four simultaneous data outputs at 2.5 Gb/s, a feature very useful in WDM networks. This is the unit we have purchased.

II. Results

The BERT is being used in a variety of experiments on a continuous basis. We have used it to evaluate performance of WDM sources purchased from Ortel Corporation, under a different grant. Typical results are summarized in the enclosed paper entitled "Hybrid and Monolithic Wavelength Division Multiplexed Transmitter Arrays", presented at the 1999 SPIE meeting in San Jose and published in the Proceedings.

We would like to draw your attention to Figures 4-7. The BERT acquired under this program made these data possible. Fig. 4 shows a schematic diagram of the experimental setup used. Quantitative comparisons between different types of transmitters are shown in Figs. 5 and 6. The BERT also allowed us to perform quantitative stability experiments of a WDM network. Fig. 7 illustrates a 1000 hr long experiment in which WDM transmission was carried out through a waveguide router. Variations in the laser wavelength during that time would have resulted in large error counts. No such events were observed, demonstrating exceptional wavelength stability.

The ability to perform quantitative evaluations of networks and interconnects made it possible for us to proceed with the establishment of a campus wide local area network in tying together eight different locations. In the star topology each location is assigned one wavelength. At this wavelength data rates can reach 2.5 Gb/s. The BERT is used to monitor the traffic and to evaluate changes in the connection quality as the network grows.

III. Personnel

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Hybrid and Monolithic Wavelength Division Multiplexed Transmitter Arrays: Performance of Commercially Available Devices

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Abstract

This paper reviews performance of hybrid and monolithically integrated WDM transmitter arrays based on directly modulated 2.5Gbps lasers, with a focus on the wavelength accuracy and stability under normal operating conditions. We also consider power stability, chromatic dispersion penalties, and the channel cross-talk. Large numbers of four-wavelength devices were obtained and evaluated under a program designed to provide university-based system researchers with advanced WDM components We show that multi-wavelength laser arrays capable of high-performance out-of-the-box operation can be now produced for research-type WDM systems.

Introduction

Multiple-wavelength laser sources are the fundamental component of WDM systems and considerable research and development effort has been devoted to their design and fabrication. The research effort, in particular, has focused on monolithically integrated multiple-wavelength laser arrays, widely believed to be a superior source, particularly in applications involving many wavelengths. However, while practically all of current commercial WDM systems rely on discrete lasers with pre-selected wavelengths, properties of such hybrid-integrated sources remain poorly documented. This divergence of research and industrial practice underscores the difficulty of producing stable, monolithic, multiple-wavelength arrays capable of meeting WDM system requirements. However, with WDM systems moving towards higher channel density and higher bit rates the virtues of the hybrid vs the monolithic approach need to be reassessed.

In the design of multiple wavelength laser arrays, either hybrid or monolithic, one has to consider a range of issues:

- *Gain material:* a typical WDM system has a 20 to 30 nm operating range in the 1.55 micron region which is defined by the Er-doped fiber amplifier (EDFA) gain window. Lasers based on quantum well structures that exhibit continuously tunable gain region of more than 200 nm might be the structures of choice [1]. More recently, there has

been also increasing interest in the use of fiber lasers in WDM applications, as their gain matches that of the EDFA [2].

- *Wavelength tuning/locking:* High quality laser sources can be readily produced using a distributed feedback grating (DFB) or a distributed Bragg reflector structure [3]. Currently most semiconductor laser arrays utilize DFB structures. With increasing number of WDM channels, the channel spacing becomes smaller and the wavelength registration accuracy requirements become more stringent. Current dense-WDM systems call for channel spacing of 50 GHz, with a GHz wavelength accuracy. In order to operate such laser arrays under different environmental and operating conditions, careful control of the temperature [4] and power are required. A number of laser designs incorporating additional build-in electrodes for wavelength tuning have been proposed [5]. In a sampled grating configuration [5a], more than 60 nm tuning was demonstrated. Wavelength stabilization through external frequency-selective feedback, provided through an external bulk grating, fiber grating, or a WDM demultiplexer, is also being investigated [6]. In addition, active frequency locking using solid state etalons, or other types of wavelength lockers, is under study for the long term wavelength stabilization of single and multiple-frequency laser sources [6a].
- *Power combining:* The use of simple 3 dB couplers to combine to combine 2^N laser sources results in the power loss, for each laser, of $N \times 3$ dB! With the use of a star coupler the loss is still $10 \times logN$. In a 40 channel WDM system, this amounts to a loss of 16 dB! As the channel number increases, it becomes desirable to use wavelength multiplexers to combine the outputs of a multiple wavelength source. The typical interference filter or fiber grating WDM multiplexer for 8 to 16 channels has a fiber to fiber loss of 2-3 dB. As the channel count increases, both the insertion loss and the cost of multiplexers increase rapidly. For large channel count applications integrated WDM multiplexers, such as arrayed waveguide grating (AWG), become a viable choice [7]. The 16-channel AWG typically have a fiber-to-fiber insertion loss of 4-6 dB and the loss increases only slightly for larger channel counts. However, impressive research results to the contrary, such devices cannot be readily incorporated into a monolithic array.

  The optical feedback is another serious issue related to power combining. While dealing with discrete lasers, one can use isolators to eliminate the optical feedback. However, isolators suitable for integrated laser arrays, in particular high channel-count laser arrays, simply do not exist and the optical feedback remains a very difficult problem.
- *Data modulation*: Current WDM systems operate at 2.5 Gbps and the data rate is moving toward 10 Gbps. To provide high quality optical signal at 2.5 Gbps and higher rates, the data should be encoded through external modulation. For individual lasers, and hybrid WDM sources, this can be readily accomplished via external EO modulators. To modulate integrated laser arrays, a monolithically integrated on-chip modulator is desirable. There has been considerable progress on integrating electroabsorption modulators with DFB lasers [9, 9a]. Electronic laser driver arrays have also been demonstrated at data rate of 2.5 Gbps and beyond [10,10a]. In hybrid integration of electronic driver chips to a laser array, via wire bonding, electrical cross-talk can be an issue.

The early integrated multiple-wavelength arrays were based on DFB and DBR two-section lasers allowing for electrical tuning [11-12]. Large laser arrays were made based on bulk [13] and strained quantum well [14-16] active layer structures. The strained structures produce lower threshold lasers with narrow linewidth and lower thermal crosstalk. These devices required either high resolution lithography to produce the proper DFB grating pitch or needed repeated holographic exposures [12]. Introduction of the phase mask was a major advancement in the lithographic mask definition [19]. E-beam lithography was also used to prepare highly accurate gratings with fine pitch shifts. To further adjust the wavelength, individual on-chip heaters were introduced [17-18].

Early WDM experiments combined the output of laser arrays into a single fiber with the use of elaborate bulk multiplexers [20]. Miniature diffraction gratings and hybrid micro-optics were introduced to simplify this process [21]. An on-chip power combining element for a three-laser array was first reported by Koren et al. [12]. An integrated optical amplifier was also provided to compensate for the combiner loss. An NxM star coupler was later used to combine the output power of a 20-wavelength laser array [22]. In a separate effort, electroabsorption modulators were inserted between the lasers and the star coupler to permit high data-rate modulation of individual lasers [23]. In both cases, an optical amplifier at the output was used to compensate for the power loss.

Although WDM multiplexer is a more efficient power combiner for a large channel-count laser array, it is quite difficult to match the MUX passband to the laser wavelength in a monolithic chip. However, the MUX can be used as a wavelength locker to generate multiple wavelength outputs. The MAGIC (multistripe array grating integrated cavity) laser [24] was the first demonstration of this concept utilizing a curved mirror grating as the wavelength selective element. The MAGIC laser not only produces multiple wavelength output, it also combines them into a single output channel [25]. The wavelength locking idea was also implemented with the arrayed waveguide grating (AWG) WDM multiplexer [26-29]. The multi-wavelength router laser can be also used as a tunable laser source. A digitally tunable laser source with build-in electroabsorption modulator has also been reported [31-32].

Finally we note the wavelength selectable fiber ring lasers using Er-doped fiber amplifier as the gain medium and an AWG for wavelength selection [2, 33]. Since the laser cavity is long, there are typically 10^3 to 10^4 axial modes within the 3 dB passband of the AWG. The laser can potentially operate multimode and thus introduce excess intermodal optical beat noise. A recent paper reported the use of a semiconductor Fabry-Perot optical amplifier as an intracavity narrow band filter to stabilize laser oscillation in a single axial mode [34].

Experimental Results

The hybrid integrated laser sources used in this work were provided by the Ortel Corp (transmitter model 10348A). The design goal was to produce two four-wavelength sources, each on an ITU grid of 3.2 nm (400 GHz), with the shortest reference wavelength of 1549.32 nm and 1550.92 nm respectively for each WDM source. Two such sources can be easily combined into an eight wavelength source or a source operating on a 200 GHz grid with wavelengths varying from 1549.32 to 1560.61 nm. Each transmitter module consisted of four independent plug-in units, each containing an

ECL compatible laser driver, a distributed feedback laser, an optical isolator, and an FC/PC fiber optic connector. Individual lasers were independently temperature and power controlled. LED indicators were provided to indicate the status of control circuitry. At the operating point, the fiber-coupled power output from each lasers was set to be greater than 2 mW. Four separate plug-ins were inserted into a rack mountable chassis to provide a DC power supply for the necessary bias voltages to each transmitter. Over one hundred such transmitters were delivered and tested.

The monolithically integrated laser arrays were obtained from Nortel Corp. Each source consisted of a monolithic four-wavelength laser array fiber-pigtailed to an array of 4 single-mode fiber. The light from the 4-laser array was simultaneously imaged through an optical system composed of 3 successive lenses and a single optical isolator. An ECL compatible laser driver was used to drive the laser at 2.5 Gbps. The laser array was mounted on a single temperature controller, with a single control circuit for the four laser array.. The fiber-pigtailed power in each fiber is more than 1 mW. The wavelength of the laser array varied between 1552.52 to 1557.36 nm in steps of 200 GHz. The DC bias current for each laser could be controlled individually.

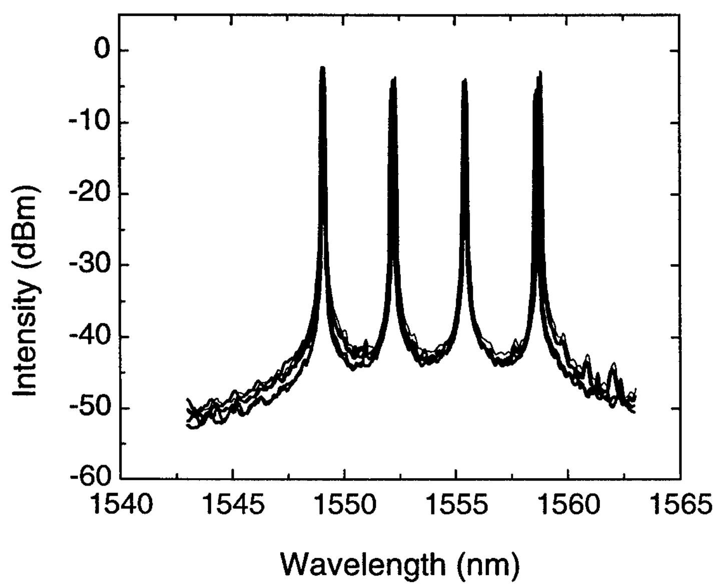

Fig. 1 A set of ten spectra obtained from hybrid four-laser WDM sources provided by the Ortel Corporation.

WDM laser transmitter modules were tested for wavelength and power stability. For the initial DC testing of hybrid arrays, light output from individual lasers was combined using a commercial 1 x 4 combiner, displayed on an optical spectrum analyzer with a resolution of 0.8 A, and stored in a computer. A spectrum from each array was obtained after a five minutes warm-up time, to allow the power and temperature control circuits to stabilize. All the arrays were tested directly after shipment from the manufacturer,

without any adjustments to control circuits. A set of spectra obtained on ten hybrid sources is shown shown in Fig.1, on a logarithmic scale. The side mode suppression better than 38 dB was measured for all the channels. The output power of the lasers, as preset by the manufacturer, showed variation of a few tenths of a dBm. The spacing between the channels was nominally 400 GHz, as specified by the manufacturer, and all the hybrid WDM units tested passed the manufacturing wavelength accuracy specification of ±0.1 nm. The control wavelength of each laser can be front panel adjusted to an accuracy of order 0.01 nm.

Test results obtained on 12 monolithically integrated arrays are shown in Table I. No temperature adjustment was performed on the array. By slightly adjusting the temperature of the arrays, a wavelength accuracy of ± 0.15 nm with respect to the ITU grid can be obtained.

Table I

Serial Number	Wavelength error versus corresponding ITU standard wavelength (nm)			
	ITU 1552.52 nm	ITU 1554.13 nm	ITU 1555.75 nm	ITU 1557.36 nm
980803-1	-0.15	0.03	0.06	-0.01
980803-2	-0.14	0.00	0.06	0.00
980803-3	-0.15	0.13	0.02	0.03
980810-1	-0.05	0.13	0.11	0.04
980810-2	-0.22	0.07	-0.12	0.03
980810-3	-0.17	0.13	-0.15	0.03
980826-1	-0.12	0.08	-0.08	-0.08
980826-2	-0.12	0.04	-0.12	-0.09
980826-3	-0.20	0.05	-0.07	0.02
980902-1	-0.27	-0.10	-0.28	-0.12
980817-1	-0.16	0.10	-0.13	-0.09
980817-2	-0.16	0.11	0.06	-0.05

More detailed temporal wavelength stability measurements, for lasers under modulation at a rate of 2.5 Gbps, are shown in Fig. 2. These measurements were carried out on a monolithically integrated array using a wavelength meter with an absolute wavelength accuracy of ± .005 nm and a display resolution of 0.001 nm. In each panel the ITU reference wavelength is indicated by a continuous line, the data is shown as dotted lines. Three of the lasers shown here are stable with time, to within 0.015 nm. The fourth device exhibits small frequency jumps, on the order of 0.02 nm, representing the digitization noise of the temperature control circuit. Similar noise events are observed in hybrid-integrated lasers.

Fig. 3 illustrates the temporal power stability of monolithically integrated devices. As expected, there is a good correlation between the wavelength and power jumps. In lasers which do not exhibit digitization noise events, the power level is maintained constant to within ~0.1 dB. However, each noise event results in a power jump of about 0.25 dB. Similar jumps occur in hybrid-integrated arrays

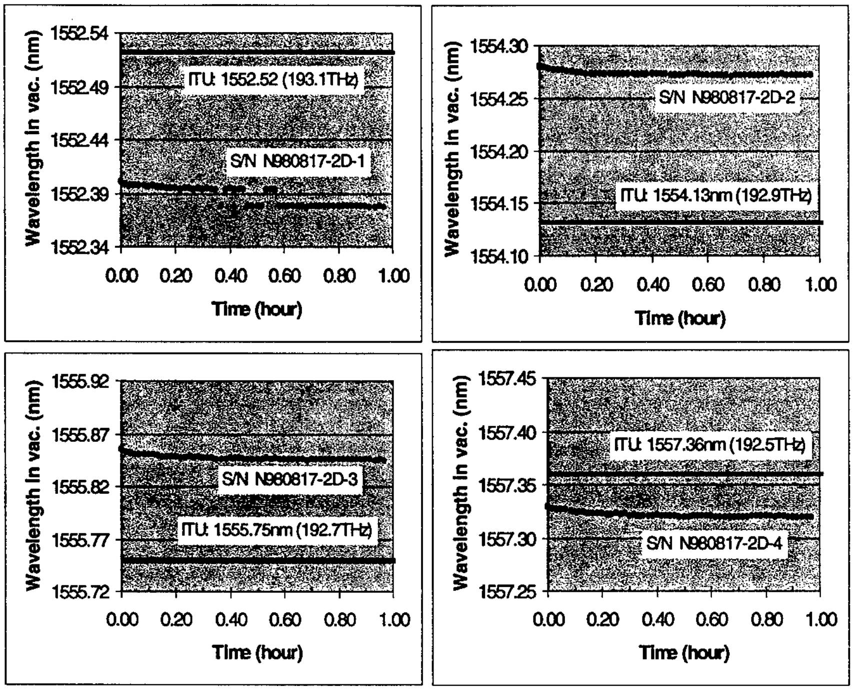

Figure 2. Wavelength stability of a Nortel monolithic laser array

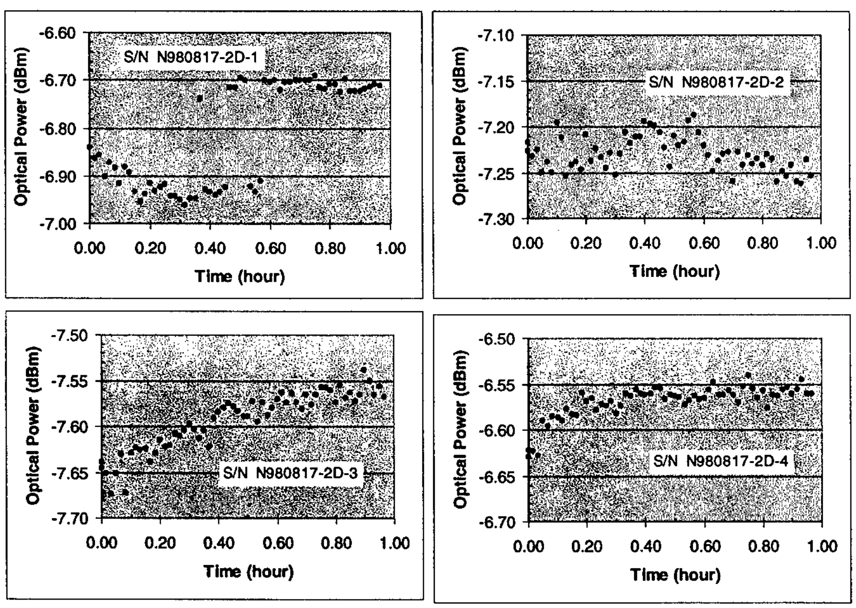

Figure 3: Temporal power stability of a Nortel monolithic laser array

Bit-error-rate measurements through 100 km of standard fiber were carried out on both types of arrays in order to evaluate the chirp penalty. This is an important consideration in closely-spaced WDM systems. Even though DFB lasers are known to have a narrow linewidth under CW conditions, these lasers will exhibit frequency chirping under modulation. This frequency chirping will lead to a dynamic broadening of the laser linewidth and, because of chromatic dispersion in a conventional fiber (i.e. Corning single mode SMF-28 fiber), will lead to a penalty in receiver sensitivity, as measured in a bit-error-rate (BER) measurement. It is therefore important to characterize WDM transmitters in a transmission measurement. BER measurements were performed on both

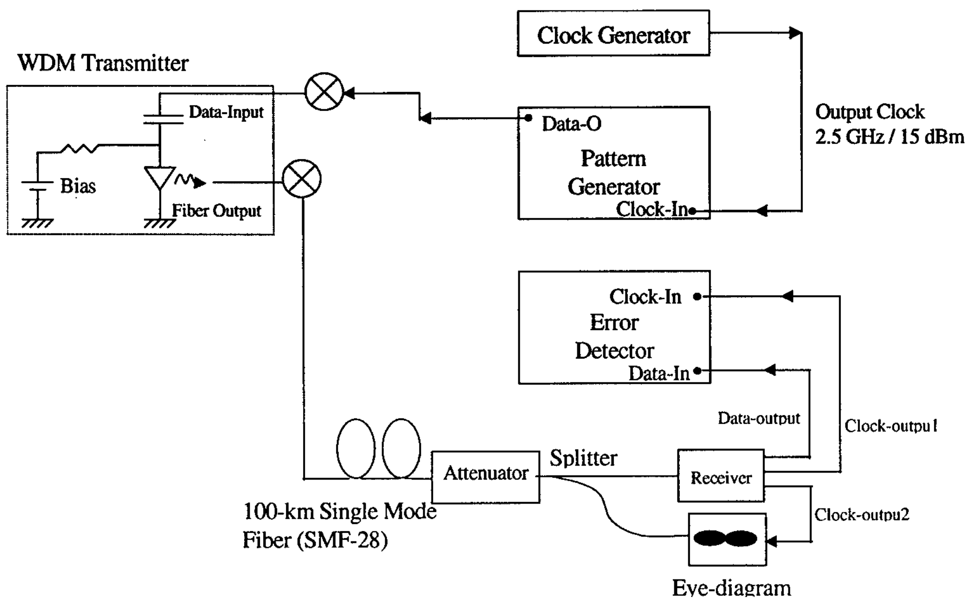

Fig. 4 Schematic diagram of a bit-error-rate measurement performed on both hybrid and monolithic WDM arrays.

hybrid and monolithic transmitters using a 100 km of Corning SMF 28 single mode fibers and a detector sensitivity assessment was performed by comparing our results at a BER = 1×10^{-9} with and without the fiber. The experimental arrangement is shown in Fig. 4 and the results for a monolithic Nortel transmitter are shown in Fig. 5 a) and b. There, it was found that the penalty could be negative, of order 1 dB, for some transmitters, indicating an improvement in the detector sensitivity. This improvement is presumably due to the sign of the created chirp, which might create some pulse compression, therefore improving the signal-to-noise. For Ortel transmitters, a penalty of order 1-2 dB was typically observed.

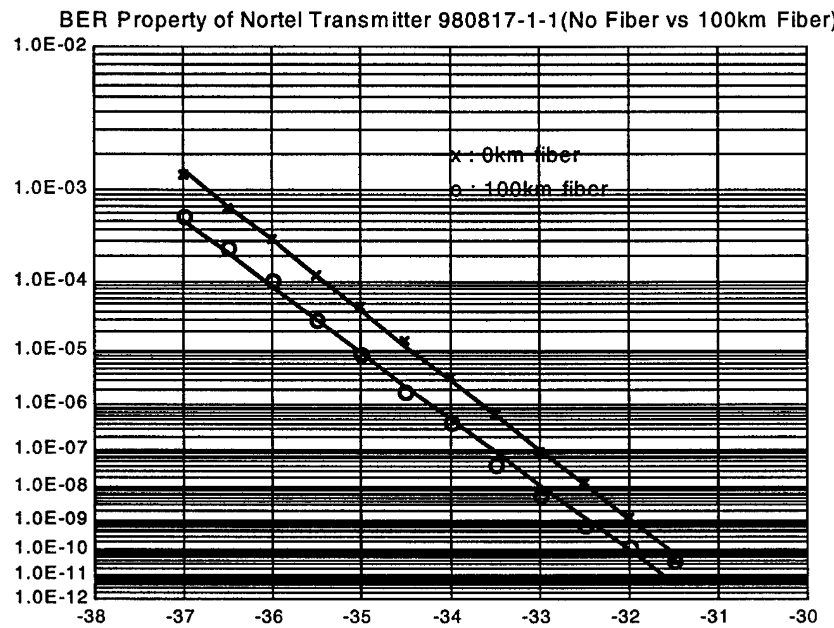

Fig. 5 Transmission experiment evaluating the chirp penalty of a monolithic WDM transmitter array

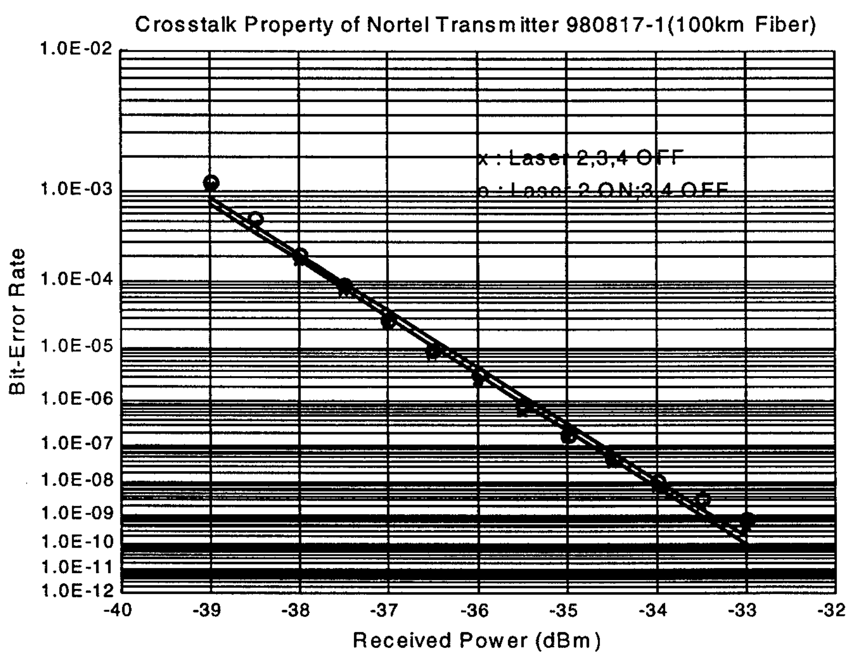

Figure 6. Crosstalk measurement on a Nortel monolithic laser array

The possibility of laser-to-laser interactions, cross-talk, might be of some concern in monolithically integrated devices. Fig. 6 shows the results of a transmission experiment designed to evaluate the degree of cross talk. The transmission experiment measured the bit error rate as a function of received power, through 100 km of fiber. The experiment was first carried out with the modulation applied only to one of the lasers, laser #1, and then repeated with both lasers #1 and #2 under modulation. The presence of cross talk would normally result in a bit-error-rate-penalty, i.e. it would produce a shift between the two lines. The experiment illustrated in Fig. 6 shows that such a penalty is indeed very small in the monolithic array and is less than 0.1 dB, of no consequence in most transmission experiments of interest. This degradation mode is absent in hybrid-integrated devices.

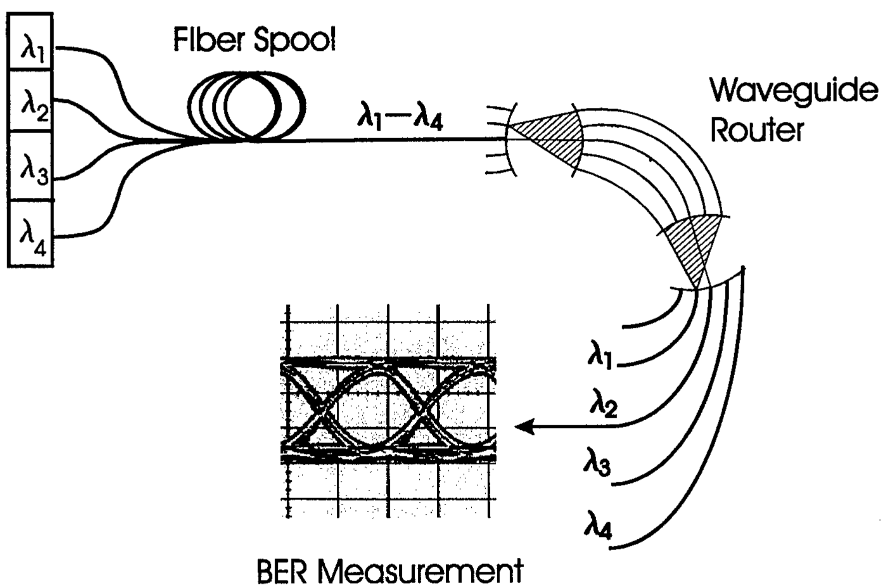

Fig. 7 Long term, 1000 hrs, transmission experiment through a waveguide router. There were no errors attributable to wavelength or power instabilities.

The final experiment, Fig. 7, illustrates performance of our lasers in a test WDM system. In this experiment the laser output from a hybrid array was first combined into a single fiber and connected to 100 km spool. The fiber was then attached to a 5 x 5 waveguide grating router used as a de-multiplexer. The router is capable of wavelength discrimination greater than 30 dB and a offers a bandpass of ~0.5.nm. Any variation in the laser output outside the bandpass of the router would result in catastrophic error rates. A receiver was then connected to the center output waveguide and the received power was adjusted to produce a bit-error-rate of 1E-9. The laser was modulated at a rate of 2.5

Gbps. The setup was allowed to run for 1000 hours and a log of BER measurements was accumulated under computer control. The highest BER recorded in that period was 6E-9.

Summary

We have investigated wavelength accuracy and stability of commercially available WDM transmitters. Large numbers of hybrid and monolithically integrated sources were tested as-delivered from manufacturers. Transmitter performance was tested under DC bias and modulation at data rates as high as 2.5Gbps. The wavelength accuracy of hybrid devices was found to be considerably better than ±0.1nm. A considerable fraction of devices tested showed small wavelength, less than 0.02 nm, and power, less than 0.1 dB, excursions due to digitization noise of control circuitry. Transmission experiments through 100 km of standard single mode fiber show low chirp penalties and, in case of monolithic arrays, the absence of cross-talk. Long term transmission experiments, up to 1000 hrs, through wavelength-selective elements simulating WDM systems do not show any penalties due to the wavelength or power instabilities. The commercial devices tested in our experiments are suitable for WDM systems research.

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